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#### **published in**

Physical Review Letters  
2009

#### **document version**

Publisher's PDF, also known as Version of record

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#### **citation for published version (APA)**

Aubert, B., Bailey, D. S., Raven, G., Snoek, H., Wang, W., & Liu, H. (2009). Search for a low-mass higgs boson in  $Upsilon(3S) \rightarrow \gamma A(0)$ ,  $A(0) \rightarrow \tau^+ \tau^-$  at BABAR. *Physical Review Letters*, 103(18), 181801.

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# Search for a Low-Mass Higgs Boson in $\Upsilon(3S) \rightarrow \gamma A^0$ , $A^0 \rightarrow \tau^+ \tau^-$ at BABAR

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(Received 15 June 2009; published 30 October 2009)

We search for a light Higgs boson  $A^0$  in the radiative decay  $Y(3S) \rightarrow \gamma A^0$ ,  $A^0 \rightarrow \tau^+ \tau^-$ ,  $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$ , or  $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$ . The data sample contains  $122 \times 10^6$   $Y(3S)$  events recorded with the BABAR detector. We find no evidence for a narrow structure in the studied  $\tau^+ \tau^-$  invariant mass region of



$4.03 < m_{\tau^+\tau^-} < 10.10 \text{ GeV}/c^2$ . We exclude at the 90% confidence level (C.L.) a low-mass Higgs boson decaying to  $\tau^+\tau^-$  with a product branching fraction  $\mathcal{B}(Y(3S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \tau^+\tau^-) > (1.5\text{--}16) \times 10^{-5}$  across the  $m_{\tau^+\tau^-}$  range. We also set a 90% C.L. upper limit on the  $\tau^+\tau^-$  decay of the  $\eta_b$  at  $\mathcal{B}(\eta_b \rightarrow \tau^+\tau^-) < 8\%$ .

DOI: 10.1103/PhysRevLett.103.181801

PACS numbers: 13.25.Hw, 11.30.Er, 12.15.Hh

In the standard model (SM) of particle physics [1], fundamental particles acquire mass via the Higgs mechanism [2]. This mechanism requires the existence of at least one new particle called the Higgs boson. In the SM, there is only a single Higgs boson, with a mass of the order of the electroweak unification scale ( $\sim 100 \text{ GeV}/c^2$ ). In the minimal supersymmetric standard model (MSSM), additional Higgs doublets are required to give mass to the new particles [3]. Moreover, in the next-to-minimal supersymmetric standard model (NMSSM), an additional Higgs singlet field is introduced to solve the hierarchy problem [4]. A linear combination of this singlet with a Higgs doublet leads to a  $CP$ -odd Higgs state,  $A^0$ , whose mass need not be larger than  $2m_b$ , where  $m_b$  is the  $b$ -quark mass [4,5]. It is ideal to search for this state in  $Y \rightarrow \gamma A^0$  decays [6]. The branching fraction  $\mathcal{B}(Y(3S) \rightarrow \gamma A^0)$  depends on the NMSSM parameters, but a value as large as  $10^{-4}$  is plausible for reasonable parameters [4]. In the mass range where the decay  $A^0 \rightarrow \tau^+\tau^-$  is kinematically accessible, this mode is expected to dominate. Constraints on the invisible [7] and dimuon [8] decays of the  $A^0$  have recently been obtained.

The current best limit on the product of branching fractions  $\mathcal{B}(Y(1S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \tau^+\tau^-)$  is given by the CLEO Collaboration [9] based on a data sample of  $21.5 \times 10^6$   $Y(1S)$  candidates. The CLEO 90% C.L. limits cover the range  $2m_\tau < m_{A^0} < 9.5 \text{ GeV}/c^2$  ( $m_\tau$  is the  $\tau$ -lepton mass [10]) and vary between  $1 \times 10^{-5}$  and  $48 \times 10^{-5}$ . A recent D0 search for a neutral pseudoscalar Higgs boson in a similar mass range showed no significant signal [11].

In this Letter, we study the decays  $Y(3S) \rightarrow \gamma \tau^+\tau^-$ , where the search for  $A^0$  is extended for a wider mass range with respect to the  $Y(1S) \rightarrow \gamma \tau^+\tau^-$ . We scan for peaks in the distribution of the photon energy,  $E_\gamma$ , corresponding to peaks in the  $\tau\tau$  invariant mass  $m_{\tau^+\tau^-}^2 = m_{3S}^2 - 2m_{3S}E_\gamma$ , where  $m_{3S}$  is the  $Y(3S)$  mass and  $E_\gamma$  is measured in the  $Y(3S)$  rest frame [center-of-mass (c.m.) frame]. We quote branching fraction values in the region  $4.03 < m_{\tau^+\tau^-} < 10.10 \text{ GeV}/c^2$ , but we exclude from our search the region  $9.52 < m_{\tau^+\tau^-} < 9.61 \text{ GeV}/c^2$ , because of the irreducible background of photons produced in the decay chain  $Y(3S) \rightarrow \gamma \chi_{bJ}(2P)$ ,  $\chi_{bJ}(2P) \rightarrow \gamma Y(1S)$ , where  $J = 0, 1, 2$ . In addition, we set an upper limit on  $\mathcal{B}(\eta_b \rightarrow \tau^+\tau^-)$ .

The data were collected with the BABAR detector [12] at the PEP-II asymmetric-energy  $e^+e^-$  storage rings at the SLAC National Accelerator Laboratory, operating at the

$Y(3S)$  resonance. We use a data sample of  $122 \times 10^6$   $Y(3S)$  events, corresponding to an integrated luminosity of  $28 \text{ fb}^{-1}$ . We also use data samples of  $2.6 \text{ fb}^{-1}$  recorded 30 MeV below the  $Y(3S)$  (OFF3S),  $79 \text{ fb}^{-1}$  at the  $Y(4S)$  (ON4S), and  $8 \text{ fb}^{-1}$  40 MeV below the  $Y(4S)$  resonance (OFF4S) to study the background and to optimize the selection criteria. These data samples were taken with the same detector configurations. Monte Carlo (MC) event samples based on GEANT4 [13] simulation of the detector are used to optimize selection criteria and evaluate efficiencies.

We select events in which both  $\tau$ -leptons decay leptonically,  $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$  or  $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$  (denoted in the following as  $\tau \rightarrow e$ , or  $\tau \rightarrow \mu$ ) [14]. Events are required to contain at least one photon with  $E_\gamma > 100 \text{ MeV}$ , and exactly two charged tracks. We allow up to nine additional photons with energies below 100 MeV in the CM frame. Photons are reconstructed from localized deposits of energy in the electromagnetic calorimeter, which have energies larger than 50 MeV in the laboratory frame and which are not associated with a charged track. Both charged tracks are required to be identified as leptons ( $e$  or  $\mu$ ). After this selection, the residual background is mostly due to  $e^+e^- \rightarrow \gamma \tau^+\tau^-$  and higher order QED processes, including two-photon reactions such as  $e^+e^- \rightarrow e^+e^-e^+e^-$  and  $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$  with smaller contributions from other  $Y(3S)$  decays and  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ).

To reduce this residual background, we exploit a set of eight discriminating variables: the total CM energy ( $E_{\text{total}}$ ) calculated from the two leptons and the most energetic photon; the squared missing mass ( $m_{\text{miss}}^2$ ) obtained from the missing four-momentum, which is the difference between the final and initial state momenta; the aplanarity ( $\mathcal{A}_{\text{pl}}$ ), which is the cosine of the angle between the photon and the plane of the leptons; the largest cosine between the photon and one of the tracks ( $\cos\theta_{\gamma\text{-track}}$ ); the cosine of the polar angle of the highest-momentum track ( $\cos\theta_{\text{track}}$ ); the transverse momentum of the event ( $p_T$ ) calculated in the CM frame; the cosine of the polar angle of the missing momentum vector ( $\cos\theta_{\text{miss}}$ ); and the cosine of the opening angle between the tracks in the photon recoil frame ( $\cos\theta_{\text{open}}$ ). The final selection criteria on these variables are obtained by maximizing the quantity  $S/\sqrt{B}$ , where  $S$  ( $B$ ) stands for the expected number of signal (background) events. Numbers of signal events are obtained from MC samples, while background yields are obtained from the OFF3S, ON4S, and OFF4S datasets. Since the background

varies as a function of the photon energy, we optimize the selection criteria in five  $E_\gamma$  regions: ( $S_1$ )  $0.2 < E_\gamma < 0.5$  GeV, ( $S_2$ )  $0.5 < E_\gamma < 2.0$  GeV, ( $S_3$ )  $1.5 < E_\gamma < 2.5$  GeV, ( $S_4$ )  $2.5 < E_\gamma < 3.5$  GeV, and ( $S_5$ )  $3.0 < E_\gamma < 5.0$  GeV. The overlaps between the  $E_\gamma$  regions reduce the discontinuity in the efficiency at the boundaries. The dominant irreducible background is due to  $e^+e^- \rightarrow \gamma\tau^+\tau^-$ . The highest level of background contaminations is observed at low  $E_\gamma$  values. Among the different final states, the background is largest in  $\tau\tau \rightarrow ee$  and smallest in  $\tau\tau \rightarrow e\mu$ .

The photon energy resolution degrades as a function of  $E_\gamma$ , from 8 MeV at  $E_\gamma \sim 0.2$  GeV to 55 MeV at  $E_\gamma \sim 4.5$  GeV. The selection efficiency is calculated using MC events. The efficiency in the  $\tau\tau \rightarrow ee$ ,  $\tau\tau \rightarrow e\mu$ , and  $\tau\tau \rightarrow \mu\mu$  modes varies as a function of  $E_\gamma$  between 10–14%, 22–26%, and 12–20%, respectively. The MC samples are generated with angular decay distributions expected for a  $CP$ -odd Higgs boson; similar efficiencies are obtained for  $CP$ -even states.

We search for an excess in a narrow region in the  $E_\gamma$  spectrum since any peak in the recoil mass ( $m_{\tau\tau}$ ), indicating the presence of a new particle decaying in  $\tau$  pairs, translates to a peak in the  $E_\gamma$  distribution. We describe the  $E_\gamma$  distribution as a smooth background spectrum and a narrow enhancement of known width, but unknown position and event yield. We perform a binned maximum likelihood fit simultaneously to the  $\tau\tau \rightarrow ee$ ,  $e\mu$ , and  $\mu\mu$  samples.

The fit is performed in two steps. First, we assume there is no signal and fit the background function. Theoretical motivations [15] inspired the choice of the background function shape,  $f = [p(1-x)^r/E_\gamma^q + s/E_\gamma^5]\beta(x) \times (3 - \beta^2(x))$ , where  $\beta(x) \equiv \sqrt{1 - 4m_\tau^2/[m_{3S}^2(1-x)]}$ ,  $x \equiv 2E_\gamma/m_{3S}$ . For each  $\tau\tau$ -decay mode, a different set of the parameters  $p, q, r, s$  is used. These parameters are allowed to vary.

The events  $Y(3S) \rightarrow \gamma\chi_{bJ}(2P)$ ,  $\chi_{bJ}(2P) \rightarrow \gamma Y(nS)$ , and  $Y(nS) \rightarrow \tau^+\tau^-$  ( $J = 0, 1, 2$ ;  $n = 1, 2$ ) are expected to peak in  $E_\gamma$  when the photon from  $\chi_{bJ}(2P) \rightarrow \gamma Y(nS)$  is misidentified as the radiative photon from the  $Y(3S)$  decay. Each of the peaks in the photon spectrum due to the  $\chi_{bJ}(2P) \rightarrow \gamma Y(1S)$  transitions is described by a crystal ball [16] (CB) function. The mean values for the  $\chi_{b0}(2P)$  and  $\chi_{b1}(2P)$  CB functions are fixed to the PDG [10], and the width values are fixed to the MC resolution, while the mean and width for  $\chi_{b2}(2P)$  are free. The power law and the transition point for all CB functions used in the analysis are fixed to the values obtained from MC simulations. The event yields for the  $\chi_{bJ}(2P)$  background for each of the three  $\tau\tau$  data samples are related via their relative efficiencies, which are functions of  $E_\gamma$ . To account for the contributions from  $\chi_{bJ}(2P) \rightarrow \gamma Y(2S)$ , a fourth CB function is added, for which the mean, width, and the relative

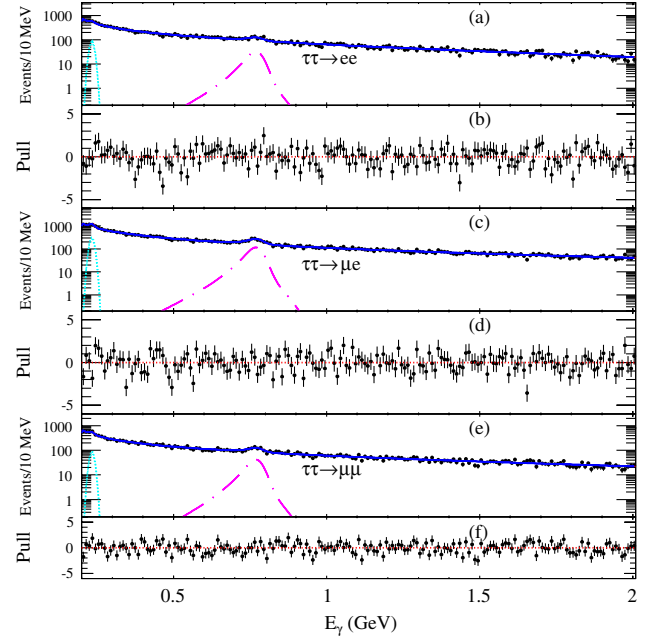


FIG. 1 (color online). (a), (c), (e):  $E_\gamma$  distributions for the different  $\tau\tau$ -decay modes. Filled circles show the data; dotted lines represent contributions from  $Y(3S) \rightarrow \gamma\chi_{bJ}(2P)$ ,  $\chi_{bJ}(2P) \rightarrow \gamma Y(2S)$ ; dotted-dashed lines show contributions from  $Y(3S) \rightarrow \gamma\chi_{bJ}(2P)$ ,  $\chi_{bJ}(2P) \rightarrow \gamma Y(1S)$ ; and solid lines show the total background function. For each  $\tau\tau$ -decay mode, the difference between the background function and the data divided by the uncertainty in the data is shown [(b), (d), (f)].

normalization are free. The fitted mean and width obtained for this peak are  $234 \pm 2$  MeV and  $13.3 \pm 2.7$  MeV (statistical uncertainties only), respectively. The number of events from the  $\chi_{bJ}(2P) \rightarrow \gamma Y(nS)$  ( $n = 1, 2$ ) contamination are common between the different  $\tau\tau$ -decay modes, and divided between these modes according to the efficiency sum,  $\epsilon^N = \epsilon_{ee} + 2\epsilon_{e\mu} + \epsilon_{\mu\mu}$ , where  $\epsilon_{ee}$ ,  $\epsilon_{e\mu}$ , and  $\epsilon_{\mu\mu}$  are the efficiencies as a function of  $E_\gamma$  in the decay modes  $\tau\tau \rightarrow ee$ ,  $e\mu$ , and  $\mu\mu$ , respectively. An example of the fits to the  $E_\gamma$  distributions in the different  $\tau^+\tau^-$ -decay modes, obtained with the selection criteria  $S_1$  and fitted in the region  $0.2 < E_\gamma < 2.0$  GeV, are shown in Fig. 1. Satisfactory fits are obtained.

In the second step of the fit procedure, we search for the signal  $Y(3S) \rightarrow \gamma A^0$ ,  $A^0 \rightarrow \tau^+\tau^-$ . We assume the  $A^0$  has negligible width [17] and parameterize the signal distribution with a CB function. The search for such a signal is performed by scanning for peaks in the  $E_\gamma$  distributions in steps that are equal to half the photon-energy resolution at any chosen value of  $E_\gamma$ . In total, 307 scan points are examined. The mean of the signal function is fixed to the photon energy at the  $i^{\text{th}}$  scan point ( $E_\gamma^i$ ). The signal width is fixed to the value of the photon-energy resolution obtained from the MC simulation. The contribution from each  $\tau\tau$ -decay mode to the total number of Higgs candidates

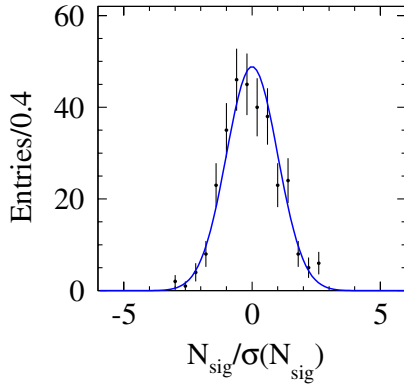


FIG. 2 (color online).  $N_{\text{sig}}/\sigma(N_{\text{sig}})$  as obtained from the scanning procedure. Only statistical uncertainties are included. The curve shows the standard normal distribution with a normalization factor of 307.

is proportional to the fractional efficiency for a particular mode. The background-shape parameters (including the  $\chi_{bJ}$  parameters) are all fixed to the values determined in the first step of the fit, with the exception of  $p$  and  $s$ , to allow free background normalization. The number of free parameters in each fit is seven ( $p_{ee}$ ,  $p_{e\mu}$ ,  $p_{\mu\mu}$ ,  $s_{ee}$ ,  $s_{e\mu}$ ,  $s_{\mu\mu}$ , and  $N_{\text{sig}}$ ), where the subscripts indicate the final state of the  $\tau\tau$ -decay modes. When the scan is performed in the regions  $S_3$ ,  $S_4$ , and  $S_5$ , the parameters  $s_{ee}$ ,  $s_{e\mu}$ , and  $s_{\mu\mu}$  are fixed to zero.

For each scan point, the yield,  $N_{\text{sig}}$ , and its statistical uncertainty,  $\sigma(N_{\text{sig}})$  are obtained from the fit. The yield significance from the data,  $N_{\text{sig}}/\sigma(N_{\text{sig}})$ , is shown in Fig. 2 and overlaid with a standard normal distribution. The data points are consistent with the normal distribution, and

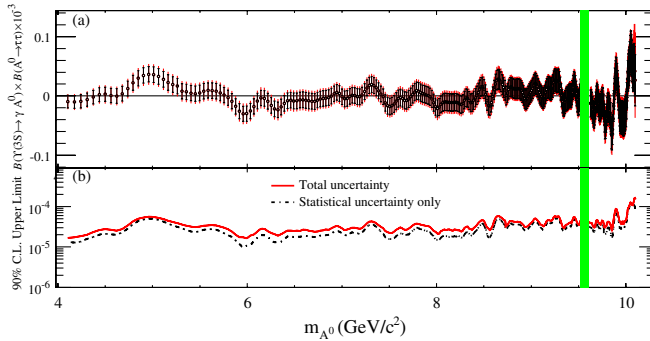


FIG. 3 (color online). (a) Product branching fractions as a function of the Higgs mass. For each point, both the statistical uncertainty (from the central value to the horizontal bar) and the total uncertainty (statistical and systematic added in quadrature) are shown (from the central value to the end of the error bar). In (b), the corresponding 90% C.L. upper limits on the product of the branching fractions versus the Higgs mass values are shown, with total uncertainty (solid line) and statistical uncertainty only (dashed line). The shaded vertical region represents the excluded mass range corresponding to the  $\chi_{bJ}(2P) \rightarrow \gamma Y(1S)$  states.

therefore no significant evidence for any unknown narrow structure is observed in the scan.

Product branching fractions are determined from the signal yields at each scan point, correcting for a fit bias described below. The results are shown in Fig. 3(a). These results show no evidence for a narrow resonance in the mass range under study. Bayesian upper limits on the product of branching fractions, computed with a uniform prior at 90% C.L., are shown in Fig. 3(b). The solid line shows the limits obtained with the total uncertainties (statistical and systematic added in quadrature) while the dashed line shows the limits with statistical uncertainties only.

We measure the branching fraction  $\mathcal{B}(\eta_b \rightarrow \tau^+ \tau^-) = (-0.1 \pm 4.2 \pm 2.3)\%$  at  $m_{\tau^+ \tau^-} = 9.389 \text{ GeV}/c^2$ , using the  $\mathcal{B}(Y(3S) \rightarrow \gamma \eta_b)$  from Ref. [18]. Therefore, the 90% C.L. upper limit on  $\mathcal{B}(\eta_b \rightarrow \tau^+ \tau^-)$  is 8 (7)%, considering all (statistical only) uncertainties and accounting for the expected 10 MeV width of the  $\eta_b$ . We note that the limit and branching fraction are insensitive to the  $\eta_b$  width within the expected 5–20 MeV range [18].

We account for systematic uncertainties due to tracking (2%), lepton identification (1.2–2.6%, depending on the  $\tau\tau$ -decay mode), photon reconstruction efficiency (4%), and the number of  $Y(3S)$  (1%). In the scan procedure, the parameters of the background shape and of the  $\chi_{bJ}(2P)$  states are fixed. To estimate the systematic uncertainty related to these parameters, each parameter is varied by its estimated statistical uncertainty determined in the first step of the fit. The scan procedure is repeated for each parameter change. When calculating the systematic uncertainties from this source, the correlations between the various parameters are taken into account. The ratio between the total systematic uncertainties due to the background shape and the statistical uncertainties varies between 12% and 170%. The largest systematic variations occur for larger values of  $m_{\tau^+ \tau^-}$ , and are due to the uncertainty in the  $q_{e\mu}$  parameter for  $\tau\tau \rightarrow e\mu$ . The fit bias and its uncertainty are determined by applying the fit procedure to a large number of MC experiments. Each MC sample contains a known number of signal events, while background events are generated according to the background shape. The event yield, returned by the fit, is a linear function of the number of input events. The event yield in the data is corrected using this function. The difference between the corrected and uncorrected event yield is (conservatively) considered as the systematic uncertainty due to the fit bias, which is typically small (few percent) but can be as large as 30% of the statistical uncertainty at high  $m_{\tau^+ \tau^-}$ . The systematic uncertainty associated with the choice of the signal shape function is determined by varying the values of the parameters in the signal CB function; the width and the power law are varied (multiplicatively) by 30% and 38%, respectively; the transition point is varied (additively) by 36%. The associated systematic

contribution is typically small (few percent) but is as large as 50% of the statistical uncertainty at large  $m_{\tau^+\tau^-}$ . Finally, we include a systematic uncertainty of 0.6% to account for the systematic uncertainty due to the  $\tau$  branching fractions [10]. The dominant systematic uncertainties are due to the background-shape parameters, which are obtained from fitting the same data sample. Thus, we conclude that the main systematic uncertainties are primarily statistical in nature.

In summary, we have performed a search for a light Higgs boson in the radiative decays  $Y(3S) \rightarrow \gamma\tau^+\tau^-$ , where  $\tau^+ \rightarrow e^+\nu_e\bar{\nu}_\tau$  or  $\tau^+ \rightarrow \mu^+\nu_\mu\bar{\nu}_\tau$ , using a data sample of  $122 \times 10^6$   $Y(3S)$  events. Our search covers the mass range  $4.03 < m_{\tau^+\tau^-} < 10.10$  GeV/ $c^2$ , excluding  $9.52 < m_{\tau^+\tau^-} < 9.61$  GeV/ $c^2$  to veto the  $\chi_{bJ}(2P)$  with  $\chi_{bJ}(2P) \rightarrow \gamma Y(1S)$ . No evidence for a signature of light Higgs boson decays to  $\tau$  pairs is observed. In this mass interval, the upper limits on the product branching fraction  $\mathcal{B}(Y(3S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \tau^+\tau^-)$  vary between  $(1.5 - 16) \times 10^{-5}$  at 90% C.L.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MEC (Spain), and STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

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